Chromatic-dispersion-free transmission using time-reversal optical parametric amplifier

H. Ou, C. Zhang, X. Xu, E. Y. Lam and K. K. Y. Wong

In this paper, we demonstrate a chromatic-dispersion-free transmission using time-reversal optical parametric amplifier (OPA) for 10-Gb/s data over 25-km of standard single-mode fiber. The time-reversal was achieved using optical phase conjugation in OPA. A pilot signal was first sent to estimate the optical channel, which would be reshaped by OPA and then retransmit with data through the same fiber. The dispersion is compensated automatically through the transmission. Experimental results showed that around 1-dB improvement can be obtained at BER < 10^{-9} compared to traditional RZ-OOK link.

Introduction: Time-reversal is a technique that can focus waves in space and time through a strongly scattering medium, which has found various applications ranging from medicine [1], to imaging [2], and to Ultra-wideband (UWB) communications etc [3]. It is also widely used in multiple-input and multiple-output (MIMO) systems to eliminate the inter-symbol interference (ISI), which is caused by multiple scattering [4]. This is closely analogous to the distortion of data propagating though single-mode fiber (SMF) caused by chromatic dispersion. In a similar way, we can achieve the chromatic-dispersion-free transmission by using the time-reversal technique.

To eliminate the effect of chromatic dispersion in (SMF), people have used electronic signal processing methods, which are quite flexible and accurate but suffer from the electronic bottleneck and can not meet the bandwidth demand in the long term [5]. To break the bandwidth limit, various optical signal processing methods emerge: people have used dispersion compensation fiber (DCF) to compensate the dispersion, which requires to control the length of the DCF [6]; fiber Bragg gratings (FBG) can also be used but with limited ability for dispersion compensation [7]; other alternatives using optical phase conjugator (OPC) have also been proposed, in which the transmission link must be symmetrical [8].

In this paper, we proposed a chromatic-dispersion-free transmission link based on time-reversal optical parametric amplifier (TROPA). The time-reversal was achieved using optical phase conjugation with an optical parametric amplifier (OPA). It is different from the previous OPA based method [8] in that there is no need to calculate the dispersion of the fiber link and send the pulse to the second fiber with similar dispersive characteristics for compensation. The distorted pulse in the proposed method is reshaped by OPA and then sent back to the same spool of fiber. The dispersion characteristics of the optical channel are first estimated by a pilot signal transmitted from the receiver to transmitter, which would be distorted after transmission. In the transmitter, the distorted pilot signal is reshaped and modulated with data by the OPC. The modulated pilot signal then transmitted to the end user via the same spool of fiber. We have shown the effectiveness of this method via experiment.

Principle and experiment: The principle of the proposed method is shown in Fig. 1a. The whole process includes three stages: first, a pilot clock signal with angular frequency ω_s transmitted from the receiver to the transmitter is used for channel estimation. In this stage, the transfer function of the SMF was estimated by the pilot signal, denoted as $H_s(\omega)$, where ω is the offset frequency of the clock signal from the optical carrier. Then in the transmitter, an idler centered at ω_i would be generated by the OPA, as is shown in Fig. 1b. The time-reversed or phase conjugated replica of the pilot signal can be expressed as $H_s{}^*(\omega)$. In the last stage, the data was modulated on the time-reversed idler and sent back to the receiver. The time-reversal communication process can be described in frequency domain as:

$$S_{Rx}(\omega) = \left(S_{Tx}(\omega) \times H_s^*(\omega)\right) \times H_i(\omega) \quad (1)$$

where $S_{Tx}(\omega)$, $S_{Rx}(\omega)$ denote the transmitted signal and the received signal, respectively, $H_i(\omega)$ represents the transfer function of SMF with angular frequency centered at ω_i. One can see from (1) that, most of the

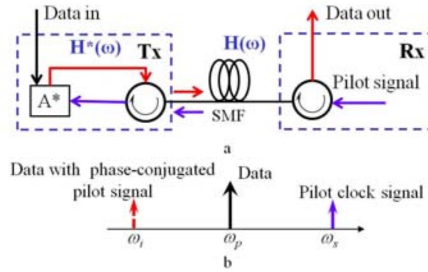

Fig. 1. *a Principle of the chromatic-dispersion-free link. Tx, Rx, and A* correspond to transmitter, receiver, and phase conjugator, respectivel b Spectrum after the OPA process.*

chromatic dispersion can be compensated via the system, leaving small parts of residual dispersion caused by the difference between ω_s and ω_i. As $\omega_s^2 - \omega_i^2 \ll \omega_i^2$, the residual dispersion is very small and could further be compensated by using orthogonal pump waves [8].

The experimental setup of the TROPA system is shown in Fig. 2. In the receiver, a 10-GHz sinewave clock signal was used to modulate the output of the continuous-wave (CW) source centered at 1570 nm via the Mach-Zehnder modulator (MZM). The bias voltage of the MZM was set to 4 V to give good extinction ratio, and a polarization controller (PC3) was used to control the polarization state of the light before it. The 3-dB bandwidth of the MZM is 10-GHz. After amplified by a L-band Erbium doped fiber amplifier (EDFA), the modulated signal was further filtered by a tunable bandpass filter (TBF) centered at 1570 nm with 1 nm bandwidth. The signal power after the TBF was measured to be +4.68 dBm. After passing through the circulator (CIR1), the signal was launched into a spool of SMF, which has a dispersion coefficient of 17 ps/nm.km. As a proof of the concept, we use a 25-km SMF in the experiment. After reaching the transmitter, the pilot signal was then coupled into the wavelength-division multiplexing coupler (WDMC1) and used as the signal in the optical parametric amplification process. In the meanwhile, the parametric pump signal was also sent to the WDMC1, with wavelength centered at 1555 nm. A 10-Gb/s $2^{13}-1$ pseudorandom binary sequence (PRBS) was modulated on the pump via another 10-GHz-bandwidth MZM. The polarization of the pump source was aligned by PC1. The bias voltage of the MZM was set to 4.5 V to give the best extinction ratio. Two EDFAs were applied to amplify the pump power, which was measured to be 26.53 dBm before the highly-nonlinear dispersion-shifted fiber (HNL-DSF). The nonlinear coefficient of the 150-m HNL-DSF was $\gamma = 0.03\text{W}^{-1}\text{m}^{-1}$, and its zero dispersion wavelength (ZDW) was λ_0 = 1554 nm. To minimize the amplified spontaneous emission (ASE) noise from the EDFA1, a TBF with 0.8-nm bandwidth was used between the two EDFAs. The pump signal was then combined with the pilot branch by the WDMC and launched together into the HNL-DSF, in which the time-reversal process occurred. PC2 and PC3 were used to align the polarizations of pump and signal before the HNL-DSF input, respectively.

The time-reversal was based on the phase conjugation in the optical parametric amplification process, during which an idler centered at

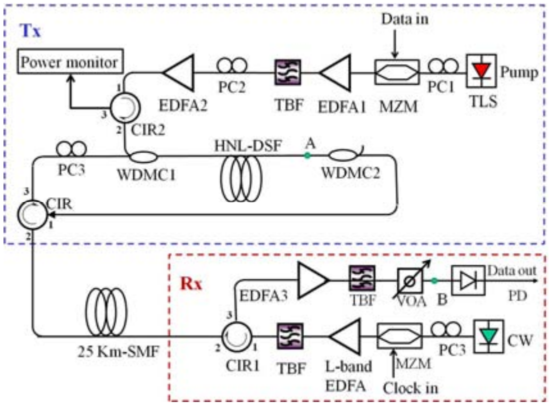

Fig. 2. *The experimental setup.*

1540 nm was generated. The time reversed idler was then filtered out by WDMC2 and launched into the 25-km SMF via the circulator and sent back to the receiver. In the receiver, the retrieved 10-Gb/s idler was then amplified to 13 dBm by EDFA3 and further filtered by TBF. The TBF with 1-nm bandwidth was used to reject excess ASE. Finally, the signal was detected and recovered by a photodiode (PD). In order to measure the BER, a variable optical attenuator (VOA) was used, with which the optical signal to noise ratio (OSNR) of the input signal can be varied.

It is worth noting that the proposed method is bi-directional, in which the pilot signal is transmitted from the receiver to the transmitter for channel estimation. This make the proposed method versatile for different transmission distances.

The eye-patterns at a received optical peak power of -20.5 dBm are shown in Fig. 3a-c, representing the result of B2B experiment, direct 25-km transmission with return-to-zero on-off keying (RZ-OOK), and 25-km transmission with time-reversal method, respectively. By a transmission through 25-km of SMF, the pattern was distorted due to chromatic dispersion in the fiber (Fig. 3b), whereas a good eye opening was achieved by using time-reversal (Fig. 3c).

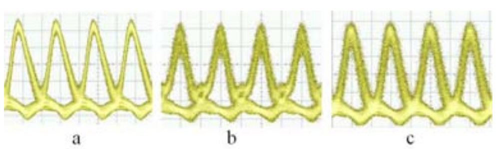

Fig. 3. *Demodulated eye-patterns of a 10-Gb/s PRBS signal. Vertical axis: 39.6 mV/div, horizontal axis: 50 ps/div*
a back-to-back transmission
b direct 25-km transmission with RZ-OOK
c 25-km transmission with the proposed time-reversal method.

We've also analyzed the BER performance against the peak received power under different transmission schemes, which is shown in Fig. 4. The direct transmission without and with the 25-km SMF are represented by the empty circle, and filled circle; while the scheme without and with 25-km SMF using the proposed time-reversal method are shown with empty triangle and filled triangle; the filled square represents the direct transmission with 25-km SMF using traditional OPA (i.e. direct optical parametric amplification without channel estimation). One can see from Fig. 4 that the dispersion-generated power penalty via a direct transmission of 25-km SMF is around 2.2 dB. The receiver sensitivity at a BER of 10^{-9} for back-to-back (B2B) experiment was -20.5 dBm. In order to measure this, we used an MZM to modulated the output of a CW laser centered at 1540 nm, to which a 10-Gb/s $2^{13}-1$ PRBS was modulated with the RZ-OOK format. Then we measured the performance of the time-reversal method based on the experimental setup shown in Fig. 2. The B2B transmission in this case showed similar performance to that with the B2B RZ-OOK, while the power penalty was further reduced to 1.2 dB with the proposed method via the transmission of 25-km SMF. The performance of the traditional OPA method via 25-km SMF was also shown in Fig. 4, which was similar to that with 25-km RZ-OOK at a BER of 10^{-9}. These results show that the proposed TROPA technique can effectively compensate

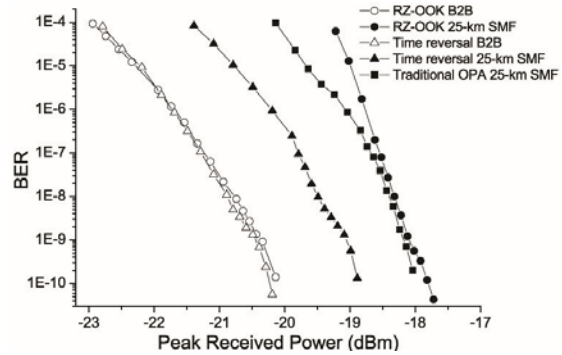

Fig. 4. *The bit-error-rate characteristics of the 10-Gb/s PRBS transmission*

the chromatic dispersion in SMF without the calculation of the total dispersion of the transmission link.

It is worth noting that, as the pump itself is modulated by the data, which limited the maximum dispersion that can be compensated. For example, if a 10-Gb/s data is modulated on the pump, then the maximum dispersion compensation TROPA can provide is around 100 ps. This problem can be solved by modulating the data with the generated idler instead of the pump itself. In this case, the maximum dispersion compensation range would no longer dependent on the modulation format of the pump.

Conclusion: We demonstrated a new chromatic-dispersion-free transmission link using time-reversal technique, which can effectively compensate the waveform distortion in a SMF. We experimentally confirmed a distortion compensation by observation of eye-patterns and BER measurements over 25-km SMF. The measured improvement is around 1 dB (at BER < 10^{-9}) compared to traditional RZ-OOK link. By further modulating the data with the generated idler instead of the pump itself, the method can updated to deal with higher dispersion-length-bandwidth system. This TROPA technique can also be used to compensate the multimode distortions in multimode fiber [9] and lead to potential use in coherent optical MIMO systems.

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H. Ou, C. Zhang, X. Xu, E. Y. Lam and K. K. Y. Wong (*Department of Electrical and Electronic Engineering, University of Hong Kong, Pokfulam, Hong Kong*)

E-mail: kywong@eee.hku.hk

H. Ou (*Institute of Applied Physics, University of Electronic Science and Technology of China, 610054, Chengdu, PR China*)

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